Estimating the Galactic center magnetic field strength from the observed synchrotron flux density

Ben Cowin [1,2]

[1] *REU Student at UCLA, Summer 2006*
Department of Physics and Astronomy
Los Angeles, CA 90095

[2] *University of Washington*
Seattle, Washington 98105

`cowinb@u.washington.edu`

ABSTRACT

Within the central few hundred parsecs of our Galaxy, a large-scale, diffuse nonthermal radio source (DNS) has been observed at several radio wavelengths. We have used the brightness distribution of this synchrotron source to model the strength and geometry of the large-scale magnetic field in the Galactic center region. A previous investigation of 330 and 74 MHz imaging data (LaRosa et al. 2005, ApJ 626, L23) concluded that the large-scale magnetic field in the region is relatively weak, only about 10 μG. However, their assumption that the magnetic field and cosmic rays are in a minimum-energy state across this region is unlikely to be valid because the ordered magnetic field implied by the vertical orientation of most of the nonthermal radio filaments observed there is inconsistent with the minimum-energy requirement that there be a substantial energy exchange between the cosmic rays and the magnetic field on time scales short compared to the energy loss time of the relativistic particles. Our new analysis of the existing DNS data abandons the minimum energy assumption, and instead assumes a cosmic ray propagation model that places the origin of the cosmic ray electrons in the Galactic disk, and invokes Liouville's theorem to yield a constant electron energy distribution function across the Galaxy, assuming that the cosmic ray electrons diffuse along the initially vertical magnetic field lines that connect the Galactic center to the disk. By tailoring the magnetic field geometry to reproduce the observed shape and intensity of the 330 MHz synchrotron emission, we find that the average field predicted by this model is at least 100 μG on a scale of several hundred parsecs, and the field peaks at approximately 500 μG at the center of the DNS.

1. Introduction

The Galactic center region continues to be a topic of intense interest in the astronomical community, with many intriguing features still in need of further study. One fundamental quantity that remains undetermined is the strength of the magnetic field in the space surrounding the center of our galaxy. Previously several attempts have been made to measure the strength of this field, but estimates span over a large range from 10 μG to 1 mG. Several authors (summarized by Morris & Serabyn 1996) have inferred a pervasive magnetic field on the order of 1 mG from observations of non-thermal synchrotron filaments detected in the region. However, the recent detection of a diffuse non-thermal source surrounding the GC (LaRosa et al. 2005, hereafter LR05) has been interpreted in terms of a much weaker field, perhaps as low as 10 μG. In this paper, we present a model of the diffuse non-thermal source observed in LR05 based on the assumption that that the energy density of cosmic rays has reached an equilibrium between the GC and the disk. By invoking Liouville's theorem, we conclude that the electron energy spectra in the GC and the disk should be nearly equal, allowing us to adopt the disk value of the spectrum for use in our model of the DNS. By matching the output of the model to the observed synchrotron flux, we are able to estimate the strength of the magnetic field near the Galactic center. Our models, which reproduce both the total flux density and the geometry of the DNS, have peak field strengths that approach significant fractions of 1 mG.

The diffuse non-thermal source (DNS) detected in LR05 was observed with the Green Bank Telescope at 330 MHz in a 20 MHz bandwidth and with a 40' beam size. The DNS approximately spans an ellipse measuring 840 by 280 parsecs across centered on the GC. The total flux density of the DNS was measured to be 7000 Jy, after subtracting an estimated 1000 Jy due to discrete sources in the region, and after subtracting a presumably constant Galactic plane contribution. In addition, the integrated flux density of the DNS at 74 MHz was estimated to be approximately 16.2 kJy, although this value is far less certain. The interpretation offered by LR05 is based on the assumption of minimum energy, from which they conclude that the average magnetic field strength over the entire 840 x 240 pc region is less than 100 μG. Furthermore, LR05 conclude that the peak magnetic field in the central 1.5° x 0.5° (210 x 70 pc) is no more than about twice as strong as the average field in the region as a whole.

While the assumption of equipartition makes calculating the magnetic field strength straightforward, there is no evidence that the Galactic center is in such a state. For the magnetic field and cosmic rays to reach an equilibrium, a process must exist to transfer energy between the two. Such a process may occur in turbulent regions having tangled magnetic fields, but the large-scale order evidenced by the population of non-thermal radio filaments is inconsistent with the presence of a tangled field. Instead, we adopt an approach that does not assume any sort of energy exchange between the field and the particles emitting synchrotron radiation.

2. Cosmic Ray Origin and Propagation

LR05 assume that the synchrotron emission is being produced by relativistic electrons that have been accelerated by recent supernovae located in the Galactic center region. These cosmic rays are thought to be effectively trapped in the region by scattering with supernova shocks as they try to escape. However, this set of assumptions is not entirely consistent with observations. The non-thermal filaments detected in the region imply a highly ordered field, with few locations available to scatter cosmic rays as they attempt to leave. The residency time for a typical cosmic ray may then be considerably less than its lifetime. A more detailed analysis of the cosmic ray sources and sinks in the region is necessary to fully determine the validity of the LaRosa group's assumption; however the mere presence of sinks in the region (in the form of molecular clouds) and the apparent shortage of shock fronts to scatter cosmic rays as they diffuse outward suggest that a different model for the propagation of relativistic electrons is needed.

We propose a model where the cosmic ray energy spectrum in the GC is very similar to the spectrum in the disk of our galaxy. Although the overall magnetic field geometry of our galaxy is not completely known, we assume that the primarily vertical magnetic field in the Galactic center is connected to the largely azimuthal field in the disk of the galaxy. Such a configuration is stable under reasonable conditions (Chandran 2001). In addition, the recent detection of the molecular loops located 3° from the Galactic center provides further evidence in support of this model. Such formations are very likely caused by a Parker instability, where the magnetic field geometry changes from vertical to azimuthal. With a magnetic field of this sort, the cosmic rays produced in the disk of the galaxy can easily diffuse to the Galactic center and vice versa, assuming the lifetime of the particle is longer than the typical travel time. According to Liouville's theorem, the particle density of cosmic rays will remain constant along magnetic field lines. Therefore, we can conclude that the cosmic ray energy spectrum in the Galactic Center region is equal to the electron distribution found in the disk of the galaxy, without making any assumptions about their origin.

One process that can affect cosmic rays is synchrotron radiation losses. Even though the magnetic field is weak, if the electrons spend enough time in transit they could lose a significant amount of energy. The energy loss of a cosmic ray electron of initial energy E_0 emitting synchrotron radiation is given by $E(t) = E_0(1 + t/t_{1/2})^{-1}$, where $t_{1/2} = (2.352 \times 10^{-3} B_\perp^2 E_0)^{-1}$ in CGS units (Moffet 1975), where $B_\perp$ is the component of the magnetic field perpendicular to the line-of-sight. For a 100 MeV electron in a 3 μG field, $t_{1/2}$ is 9.3×10^9 years. Assuming that the cosmic rays diffuse at the Alfvén speed, which is approximately 200 km/s in the Galactic halo for a field strength of 3 μG and density of 10^{-3} atoms cm^{-3} (Parker 1992), and that a cosmic ray must traverse 30 kpc to get from the disk to the GC (a distance that is conservatively large), the total time a particle spends in the galactic halo is 1.425×10^8 years. Thus the synchrotron energy losses for particles near 100 MeV are relatively small and can be ignored. Since the total particle density of cosmic rays is constant along field lines, and the energy losses are negligible, then the spectrum of cosmic rays in the Galactic center is essentially equal to the cosmic ray spectrum in the disk of the galaxy. This conclusion is consistent with the observation that the energy density of cosmic ray protons in the Galactic center appears to be almost equal to that measured in interstellar space near the sun, as determined from gamma ray emission and elemental abundances (see references in LR05 Section 3.2).

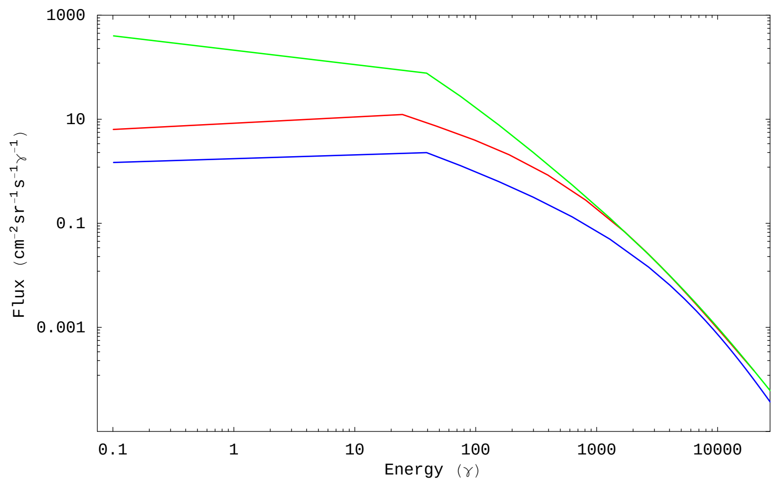

Fig. 1.— The rough approximations of the three different electron spectra used in the synchrotron models presented here. The red line represents the Strong spectrum, the blue line the Disk spectrum, and the green line the Polar spectrum. γ is the relativistic Lorentz factor.

3. Synchrotron Emission Model

The strength of synchrotron emission depends essentially upon two variables, the electron energy spectrum and the strength of the magnetic field in the region. For the magnetic field, we will start from a current distribution in an attempt to be as realistic as possible about the magnetic field characteristics. The current and magnetic field calculations will be described in the Appendix. Since the Galactic center electron spectrum is expected to be comparable to the electron spectrum in interstellar space near the sun, this spectrum can be used to create a synchrotron emission model for a given magnetic field strength. However, although the electron flux is well-known for energies greater than approximately 1 GeV, the low-energy portion of the electron spectrum which is most important to our model has not been measured, since these electrons are unable to penetrate our solar system. Fortunately, several models of the electron flux in the appropriate energy range have been created using various assumptions about the sources and propagation methods involved. We considered three different electron spectra that cover a wide range of possibilities for the low-energy electron region. Two of the models are taken from Langner et al. (2001), where the spectra are determined primarily by considering the synchrotron emission from the Galactic disk in one model and from the polar region of the galaxy in the other. The third model we considered comes from Moskalenko & Strong (1998) and includes the propagation of primary electrons and the creation of secondary electrons from other processes. These models are shown in Figure 1.

A single electron emitting synchrotron radiation has a spectrum given by

$$P(\gamma, \nu) = 4\pi \cdot 1.865 \times 10^{-23} B_{\perp}(\nu/\nu_c) \int_{\nu/\nu_c}^{\infty} K_{5/3}(\eta) d\eta \text{ ergs/s} \tag{1}$$

where all values are in cgs units and $K_{5/3}$ is a modified Bessel function (Moffet 1975). The critical frequency ν_c is defined as $6.266 \times 10^{18} B_{\perp} E^2$. To find the synchrotron emission from an ensemble of electrons, the spectrum of one electron must be obtained by integrating the emissivity over all electron energies. The final expression for synchrotron emission per unit volume in a particular frequency range is given in Equation 2.

$$L(\nu_1, \nu_2) = \int_{\nu_1}^{\nu_2} d\nu \int_{1}^{\infty} d\gamma \cdot 2.14 \times 10^{-4} N(\gamma) P(\gamma, \nu) \text{ ergs/s/m}^3 \tag{2}$$

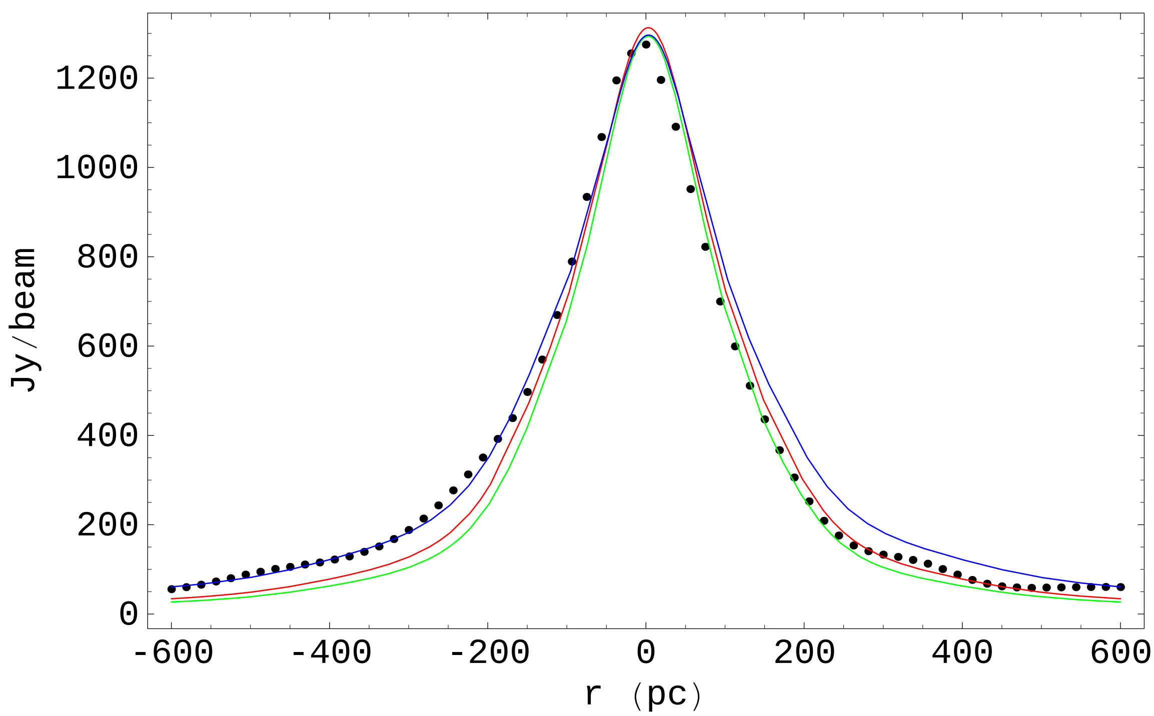

Fig. 2.— The synchrotron flux density measured along the plane of the galaxy. The black points are the actual data, the red line is the Strong model, the blue line the Disk model, and the green line the Polar model.

With Equation 1 for the synchrotron output, the only variable left to determine is the magnetic field. Since the electron energy spectrum and total energy density are assumed to remain constant over the entire region, the strength of the magnetic field must vary to produce the strongly peaked

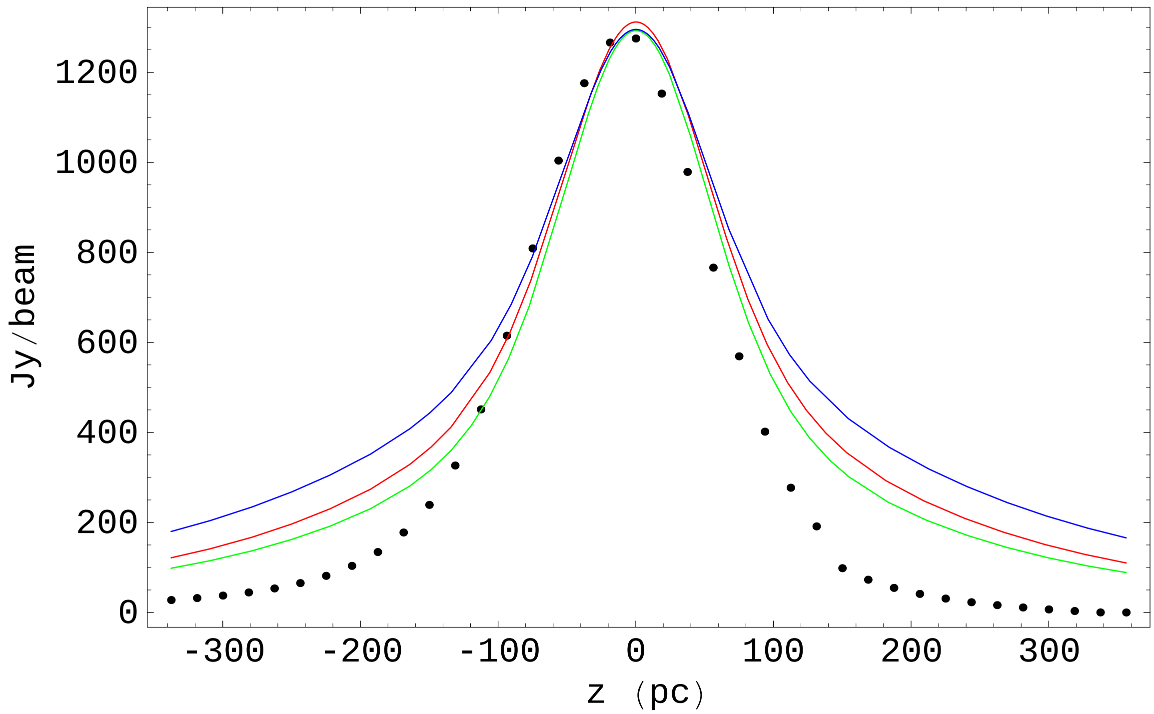

Fig. 3.— The synchrotron flux density measured along the vertical axis. The black points are the actual data, the red line is the Strong model, the blue line the Disk model, and the green line the Polar model.

radio emission detected by LaRosa et al.. With the assumption of cylindrical symmetry, it was possible to create a current distribution (see Appendix A) that corresponds to a magnetic field that closely matches the observed synchrotron output. Using Mathematica, the synchrotron emission was calculated at grid-points spaced 10 pc apart throughout the Galactic center region. The GBT image also includes approximately 1000 Jy of emission due to point sources, catalogued in LaRosa et al. (2000). The strongest of these sources were added to our synchrotron model. The resulting 2-dimensional image was then convolved with a Gaussian having FWHM of 40 arcsec, the beam width of the GBT. By adjusting the strength of the magnetic field, it was possible to match both the overall shape of the observed synchrotron emission as well as the total flux density of the DNS. This procedure was followed for each of the three electron spectra outlined above, yielding slightly different results for each case. Figures 2 and 3 shows how well the three models match the observed synchrotron emission (after the subtraction of the Galactic plane emission), both along the planar axis of the galaxy and perpendicular to that plane.

In addition to the 330 MHz observations, the LaRosa group also estimated the 74 MHz flux density in the same region to be approximately 16.2 kJy. The DNS has also been observed at 3 GHz, with a flux density of 1520 Jy (Cooper & Price 1964). Table 1 shows the synchrotron emission flux density predicted by each of our electron spectrum models compared to the observed values.

Table 1: Synchrotron Flux Density (Jy)

Model	**74 MHz**	**330 MHz**	**3 GHz**
Strong	16500	9100	2600
Disk	14600	10500	4800
Polar	18100	8100	2100
Observed	16200	7000	1520

In general, the synchrotron emission predicted by our models is slightly higher than the actual measured flux density. Most of this excess is likely from locations at large distance above and below the plane of the galaxy, where the predicted synchrotron emission strength is significantly larger than the observed data. This phenomenon can clearly be seen in Figure 3. This suggests that the geometry chosen for our current/magnetic field may not be the best choice, although the emission peak matches up quite well. Still, the results of our model are clearly comparable to the observed flux densities measured for the DNS. It is possible that much of this discrepancy could be removed by relaxing the assumption of a constant electron energy spectrum.

4. Conclusions

The magnetic field needed to produce the synchrotron emission in our models is significantly larger than the 10 μG estimated by LR05. In their paper, the LaRosa group considered the magnetic field strength in two elliptical regions, a large one measuring 840 x 240 pc, and a smaller one measuring 210 x 70 pc along the semimajor axes. Table 2 compares the average magnetic field strength in each of these regions between the various synchrotron models used above and the LaRosa minimum energy value.

Table 2: Average Magnetic Field Strength (μG)

Model	**Large Ellipse (840 x 240 pc)**	**Small Ellipse (210 x 70 pc)**
Strong	149	448
Disk	319	960
Polar	128	385
LaRosa Minimum Energy	<100	<200

There is a discrepancy of over an order of magnitude between the magnetic field values predicted by the synchrotron models given here and the 10 μG estimate from the minimum energy analysis carried out in LaRosa et al. The conclusion based on the synchrotron models presented here is that the magnetic field strength in the Galactic center region is somewhere around 100-500 μG, depending on the exact electron spectrum used in the model. This is right in the middle of the two extreme estimates of 10 μG and 1 mG predicted from various other observations. Although our interpretation relies on the assumption of a relatively low electron energy density than might be expected in the GC, this may still be a more reasonable model than one based on the assumption of energy equipartition, despite the large uncertainties in both the cosmic ray spectrum and the current distribution. We conclude from this that the large-scale magnetic field in the Galactic center region is at least 100 μG, and perhaps peaks at a sizable fraction of 1 mG.

Much further work is needed to refine the estimate of the magnetic field strength presented here. A greater understanding of the sources and sinks for cosmic rays in the Galactic center is necessary to understand the importance of local sources versus the incoming cosmic ray flux from the rest of the galaxy. In addition, synchrotron energy losses as the particles transit from the disk to the Galactic center could have an impact on the electron energy spectrum used in the synchrotron models. New information on the global structure of the galactic magnetic field could provide insight into the propagation of cosmic rays from the disk to the Galactic center. A future model of the DNS might include cosmic ray diffusion, including local sources and sinks to determine the exact characteristics of the electron energy spectrum in the Galactic center. Such an analysis would be extremely valuable for providing further constraints on the magnetic field strength in the Galactic center region.

A. Derivation of the Magnetic Field

The magnetic field used in the above model was created through the process outlined in Labinac et al. (2006) for calculating the field of a cylindrical shell of current. Although it would have been possible to postulate the approximate geometry of the magnetic field without starting from the current distribution, by stepping through this process it becomes clear that the field geometry used in our model for the synchrotron emission can arise from a reasonable and relatively simple axisymmetric current distribution in the galactic center region. This guarantees that the resulting magnetic field models be physically plausible. Our calculation of the field deviates from that of Labinac et al. in that, while they considered a cylinder of constant current density, we allow the current to change with position, such that $I(\rho, z) = I_0 P(\rho) Z(z)$, where ρ, z and ϕ define position in cylindrical coordinates: the z-axis is taken to be perpendicular to the plane of the galaxy and ϕ is the angular coordinate. Note that the current does not depend on ϕ, preserving the cylindrical symmetry of the current distribution.

Before deriving an expression for the magnetic field, the functions $P(\rho)$ and $Z(z)$ must be given explicit functional forms. Although there are several reasonable possibilities for these dependences, we chose a model where the current density decreases as a Gaussian along the z-axis and falls off as a power law in the radial direction. Initially a current configuration was investigated in which $P(\rho) = 0$ inside of some critical ρ_0 value. However, the strong peak in the synchrotron emission measured by LaRosa et al. (2005) implies that the magnetic field is strongly peaked as well since the cosmic ray emissivity remains constant. This rules out a model in which $P(\rho < \rho_0) = 0$, since that would create a minimum in the field strength at the very center. Instead, a model was adopted in which $P(\rho)$ has a constant value inside of ρ_0 and falls off as a power law outside of that region.

A similar structure was built into $Z(z)$, where the function remains constant inside of $z = \pm z_0$ but falls off as a Gaussian elsewhere. Two parameters were created to adjust the exact dependence of the current distribution. For the radial dependence, α controls the strength of the power law, while β corresponds to a typical scale height of the current, such that the full-width at half maximum (FWHM) of the distribution equals 2.3548β (Equation A2).

$$P(\rho) = \begin{cases} 1 & \text{if} \quad 0 \leq \rho \leq \rho_0, \\ (\rho/\rho_0)^{-\alpha} & \text{if} \quad \rho > \rho_0. \end{cases} \tag{A1}$$

$$Z(z) = \begin{cases} e^{-(z+z_0)^2/2\beta^2} & \text{if} \quad z < -z_0, \\ 1 & \text{if} \quad -z_0 \leq z \leq z_0, \\ e^{-(z-z_0)^2/2\beta^2} & \text{if} \quad z > z_0. \end{cases} \tag{A2}$$

With an explicit form for $I(\rho, z)$, the magnetic field can now be calculated. As in Labinac et al., we start with the vector potential of a single loop of current having radius ρ' at height z' relative to the coordinate axes:

$$\mathbf{A}(\mathbf{r}) = \frac{\mu_0}{4\pi} \int \frac{\mathbf{J}(\mathbf{r}')}{|\mathbf{r} - \mathbf{r}'|} d\tau', \text{ where } \mathbf{J}(\mathbf{r}') \text{ is the current density.} \tag{A3}$$

To evaluate this integral in cylindrical coordinates, it becomes convenient to expand $1/|\mathbf{r} - \mathbf{r}'|$ in terms of Bessel functions, the details of which can be found in Labinac et al.. The expansion is expressed in terms of an integral over a new parameter, k, which also appears inside the Bessel functions. After some simplification, the vector potential at (ρ, z) due to a single current loop located at ρ',z' reduces to Equation A4, where J_1 is a Bessel function of the first kind:

$$A_\phi(\rho, z, \rho', z') = \frac{\mu_0 \rho' I_0}{2} \int_0^\infty P(\rho') Z(z') J_1(k\rho) J_1(k\rho') e^{-k|z-z'|} dk \tag{A4}$$

To find the total field produced in the galactic center region, the contribution to the vector potential for a single current loop must be integrated over ρ' and z'. The complete integral that must be evaluated is:

$$A_\phi(\rho, z) = \frac{\mu_0 I_0}{2} \int_0^\infty dk \int_0^R d\rho' \int_{-L/2}^{L/2} dz' \rho' P(\rho') Z(z') J_1(k\rho) J_1(k\rho') e^{-k|z-z'|}, \tag{A5}$$

where R and L are parameters that describe the extent of the region containing the current. In all of the models considered, R and L were taken to be 1000 pc.

The integrals over ρ' and z' are somewhat tedious, but they are possible to evaluate. Then all that remains to be done is to take the curl of Equation A5, $\mathbf{B} = -\frac{\partial A_\phi}{\partial z}\hat{\rho} + \frac{1}{\rho}\frac{\partial}{\partial \rho}(\rho A_\phi)\hat{z}$, producing equations for B_ρ and B_z in terms of integrals over k. To evaluate these expressions, Mathematica was used to numerically integrate the integrals at a finite number of ρ and z values, and then a cubic interpolation was applied elsewhere. By using 121 reference points, this interpolation method proved to be very accurate in matching the precise values produced by the numerical integration routine, but completed the calculation in a small fraction of the time. The resulting expressions for B_ρ and B_z were then used in the synchrotron emission model above, with α and β being constrained by the observed emission from the Galactic center.

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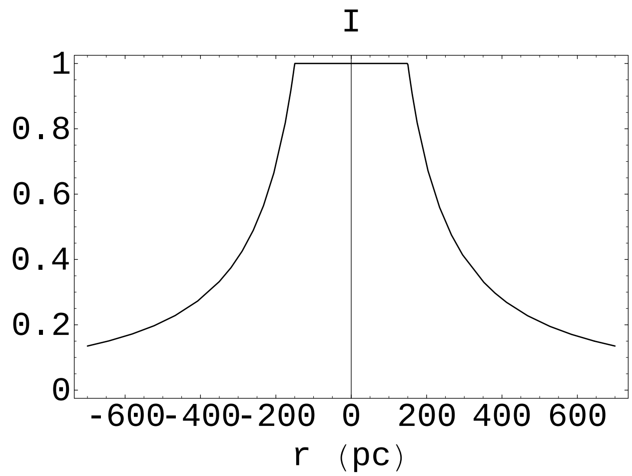

Fig. 4.— The normalized current distribution along the radial axis.

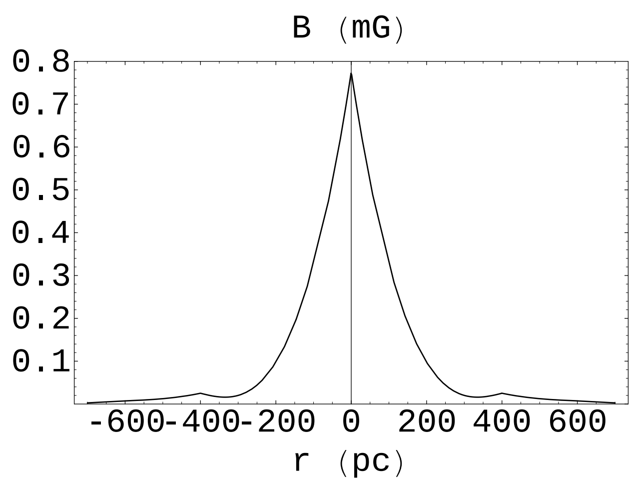

Fig. 5.— The strength of the magnetic field required to reproduce the DNS using the Strong electron spectrum, plotted along the radial axis.

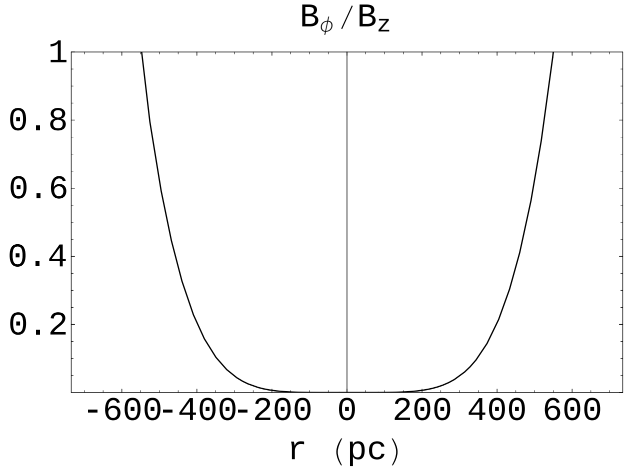

Fig. 6.— The assumed ratio of the azimuthal component of the magnetic field to the vertical component. For the majority of the region under consideration, the azimuthal component is considered to be negligible.

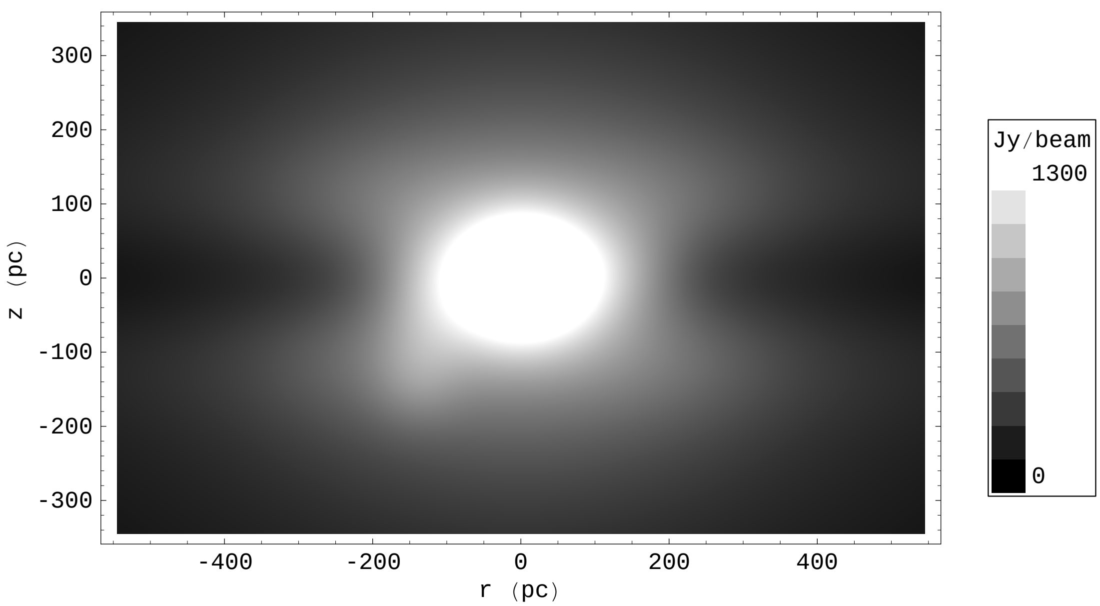

Fig. 7.— The predicted flux density of the DNS.